

# Double Longitudinal Spin Results and $\Delta G$ at PHENIX

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RHIC & AGS Users' Meeting

# Outline

- Introduction
- Variety of  $A_{LL}$  Probes
- Global Analysis and  $\Delta G$  Extraction
- Relative Luminosity Issues and Studies

# Sum Rules

- **Charge** sum rule
  - assumes zero strangeness

$$Q_{proton} = 1 = \int_0^1 dx \left( \frac{2}{3}[u(x) - \bar{u}(x)] - \frac{1}{3}[d(x) - \bar{d}(x)] \right)$$

- **Momentum** sum rule
  - quark term from neutrino, antineutrino x-section measurements
    - <50% of momentum
      - conclude that gluon contributes >50% of linear momentum

$$P_{proton} = P_{quark} + P_{gluon}$$

$$= \int_0^1 dx \, x \left( [u(x) + \bar{u}(x)] + [d(x) + \bar{d}(x)] + [s(x) + \bar{s}(x)] \right) + \int_0^1 dx \, x g(x)$$

- **Spin** sum rule
  - quark spin, gluon spin, OAM
  - DIS experiments find quark spin contribution only 25-35%

$$S_{proton} = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$

$$\Delta G = \int_0^1 dx \, \Delta g(x), \quad \Delta \Sigma = \int_0^1 dx \, ([\Delta u(x) + \Delta \bar{u}(x)] + [\Delta d(x) + \Delta \bar{d}(x)] + [\Delta s(x) + \Delta \bar{s}(x)])$$

quark



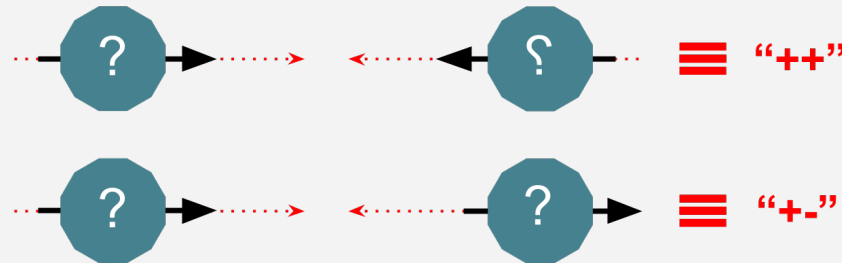
quark,  
gluon



quark,  
gluon,  
OAM

# Double Longitudinal Helicity Asymmetries

- In p+p scattering:
  - proton spin parallel (positive helicity) or antiparallel with its momentum vector:

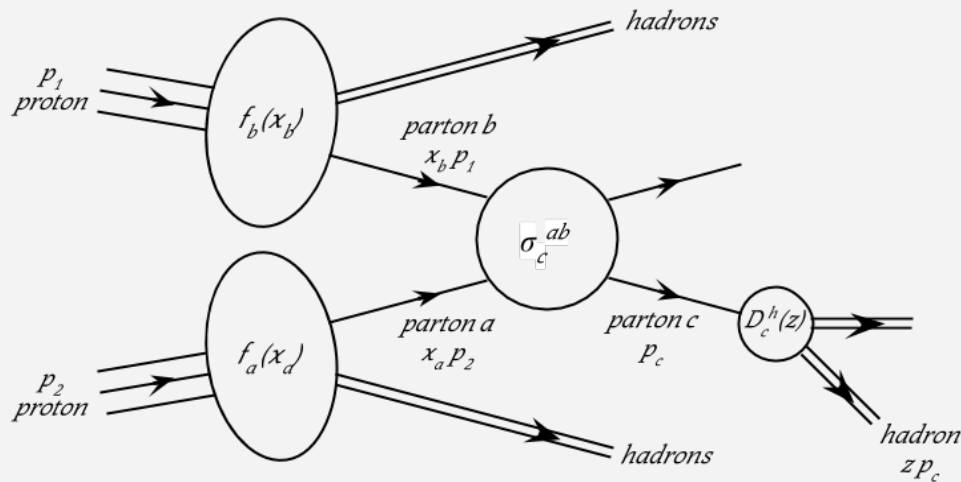


- “Double Longitudinal Spin Asymmetry” then defined in terms of cross-sections:

$$A_{LL} = \frac{(\sigma^{++} + \sigma^{--}) - (\sigma^{+-} + \sigma^{-+})}{(\sigma^{++} + \sigma^{--}) + (\sigma^{+-} + \sigma^{-+})}$$

- Can be similarly defined for fixed target experiments

# Double Longitudinal Experiments: p+p



- p+p scattering
- Known a priori:
  - parton-parton cross sections (calculable in pQCD)
  - *including gluon scattering!*
- Ingredients from other experiments:
  - Fragmentation functions (from e+e-)
- Assume “factorization:”

$$A_{LL} = \frac{\sum_{abc} \Delta f_a(x_1, \mu_F^2) \otimes \Delta f_b(x_2, \mu_F^2) \otimes \Delta \sigma^{a+b \rightarrow c+X}(x_1, x_2, p_c, \mu_F^2, \mu_R^2, \mu_{FF}^2) \otimes D_c^h(z, \mu_{FF}^2)}{\sum_{abc} f_a(x_1, \mu_F^2) \otimes f_b(x_2, \mu_F^2) \otimes \sigma^{a+b \rightarrow c+X}(x_1, x_2, p_c, \mu_F^2, \mu_R^2, \mu_{FF}^2) \otimes D_c^h(z, \mu_{FF}^2)}$$

Diagrammatic annotations for the equation above:

- A red box around  $\Delta f_b(x_2, \mu_F^2)$  has an arrow pointing to a box labeled "polarized PDF".
- A red box around  $\Delta \sigma^{a+b \rightarrow c+X}$  has an arrow pointing to a box labeled "partonic reaction a+b -> c".
- A red box around  $\sigma^{a+b \rightarrow c+X}$  has an arrow pointing to a box labeled "partonic x-sect".
- A red box around  $D_c^h(z, \mu_{FF}^2)$  has an arrow pointing to a box labeled "fragmentation function".

- Factorization tested in each case by checking denominator against absolute x-section

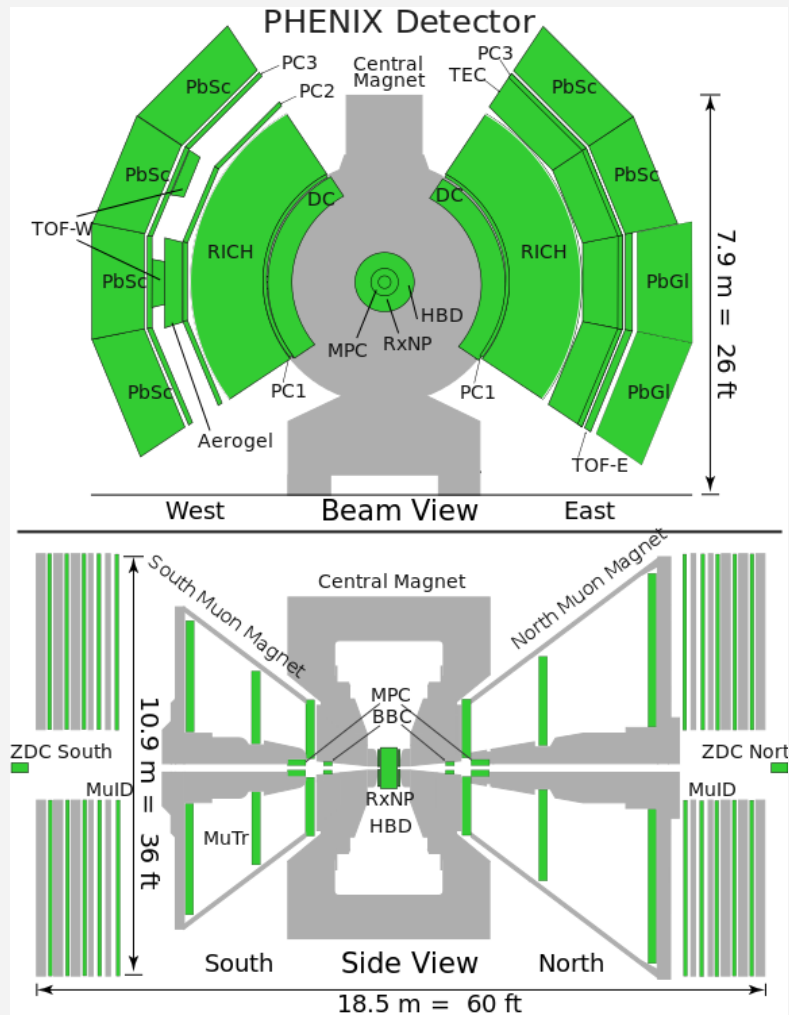
# The PHENIX Experiment at RHIC

## Central arms

- $|\eta| < 0.375$ ,  $\Delta\phi = (\pi/2) \times 2$
- Tracking
  - Drift Chamber (Multi-Wire Proportional)
  - Pad Chambers
- Particle ID
  - Ring Imaging Cherenkov detector
  - Hadron Blind Detector (Gas Electron Multiplier) in '09 and '10
- EM Calorimetry
  - Two separate technologies for cross-check
  - Lead-Scintillator (PbSc)
    - sampling calorimeter
  - Lead-Glass (PbGl)
    - Cherenkov radiation calorimeter

## Forward arms

- Tracking, Calorimetry, Muon Identification
- Minbias detectors
  - Zero Degree Calorimeter:
    - $|\Delta\eta| = > 6$ ,  $|z| = 18\text{m}$ 
      - outside of bending field, sees neutrals
  - Beam-Beam Counter:  $\Delta\eta = \pm(3.1 \text{ to } 3.9)$ ,  $|z| = 1.4\text{m}$ 
    - reconstruct collision z-vertex online with  $\sim 5\text{cm}$  resolution

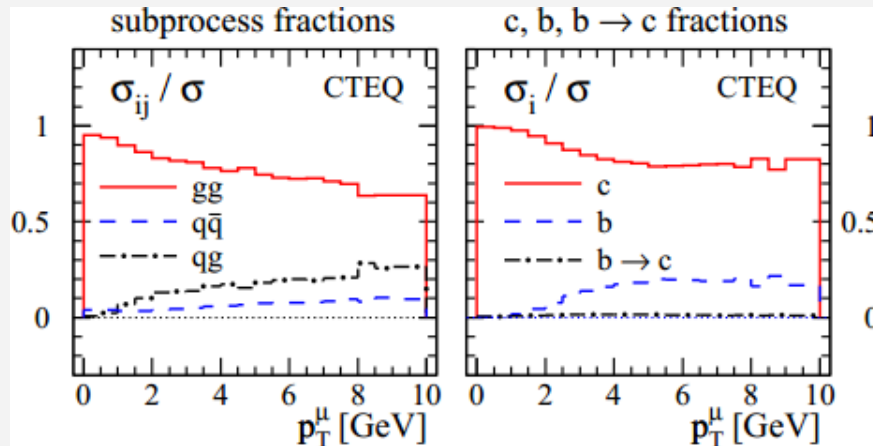


# Final-state Probes for $A_{LL}$

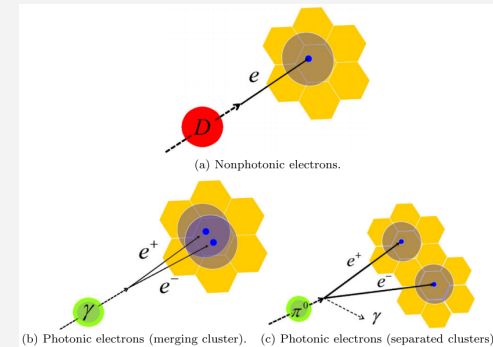
- PHENIX is a versatile detector that allows  $A_{LL}$  measurements from a variety of complementary probes, including:
  - Single electrons from heavy flavor decays
    - dominated by gluon-gluon scattering
  - Electromagnetic clusters at forward rapidity
    - low Bjorken- $x$  reach
  - Identified charged pions
    - sensitivity to sign of  $\Delta G$
  - $\pi^0$  pairs
    - improved  $x$  resolution through correlation
  - Neutral meson decays
    - statistically powerful probe

# Probe: Heavy Flavor Decays

- Analysis of electrons (positrons) from Heavy Flavor Decays
- Dominated by gluon-gluon scattering resulting in a c-cbar pair

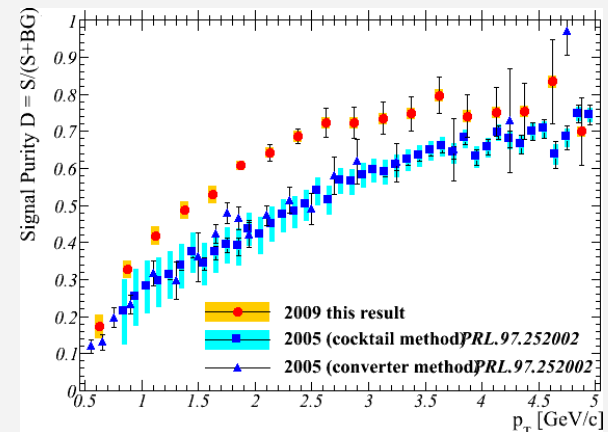


- Measure electron from decay of heavy flavor meson
  - e.g.

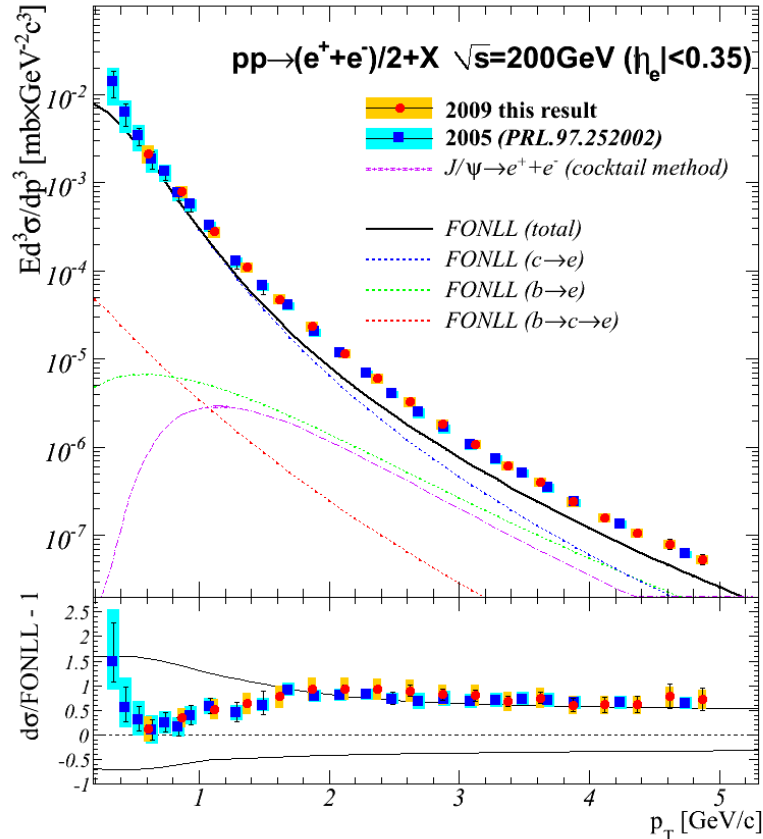


- Improved BG rejection with Hadron Blind Detector in Run9

- Cherenkov Radiator/GEM detector, 50 cm from IR
- 6.2 cm<sup>2</sup> pads, circle from electron rad. slightly larger than 1 pad

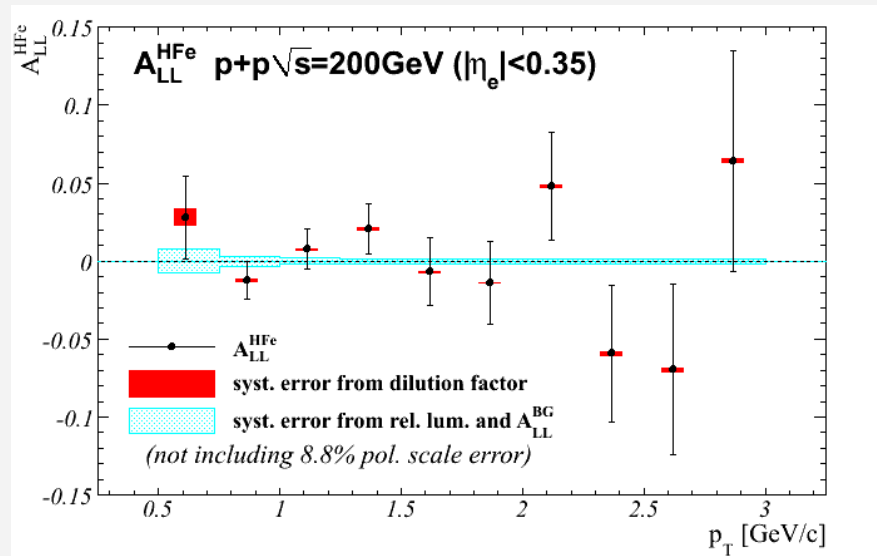


# Probe: Heavy Flavor Decays



- cross section measurement at upper limit of theory uncertainty

- gluon-gluon scattering:
  - sensitive to magnitude of  $\Delta g$
  - negligible quark scattering contribution to asymmetry

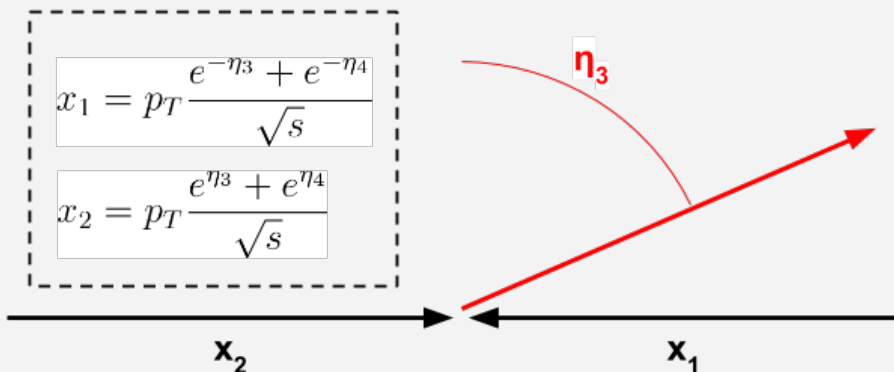


- resultant constraint:

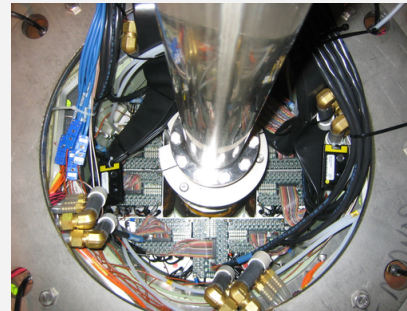
$$|\Delta G^{[0.01,0.08]}| < 0.85 \text{ (1}\sigma\text{)}, \mu = 1.4 \text{ GeV}/c^2$$

# Probe: EM Clusters at Forward Rapidity

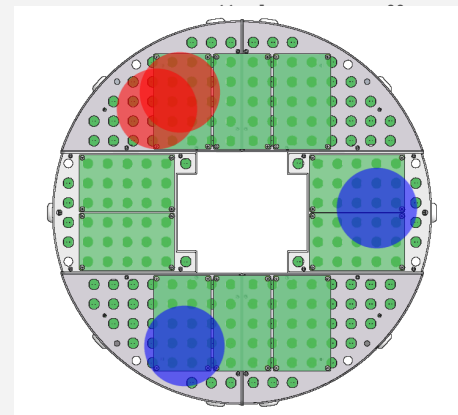
- Forward  $A_{LL}$  allows access to lower Bjorken- $x$ 
  - for partonic reaction  $1+2 \rightarrow 3+4$ :



- Measurement of high statistics forward  $\pi^0$  production
- Can extend PHENIX  $\Delta G$  reach down to  $x \sim 0.002$ 
  - central arm  $\pi^0$  down to  $x \sim 0.02$



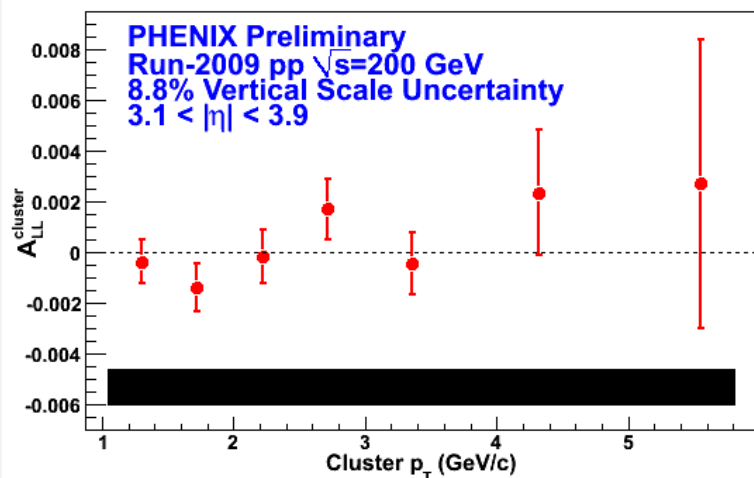
- Muon Piston (EM) Calorimeter
  - $3.1 < |\eta| < 3.9$ ,  $\Delta\phi = 2\pi$
  - $4.8 \text{ cm}^2$  towers
  - $\pi^0 \rightarrow \gamma\gamma$  measurement limited by merging at  $p_T \gtrsim 2 \text{ GeV}/c$ 
    - analyze unidentified electromagnetic



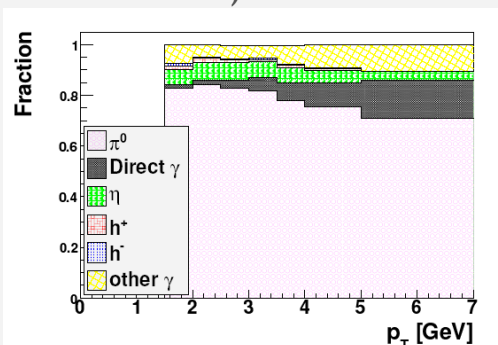
$\pi^0$  meson decay  
 $\eta$  meson decay

# Probe: EM Clusters at Forward Rapidity

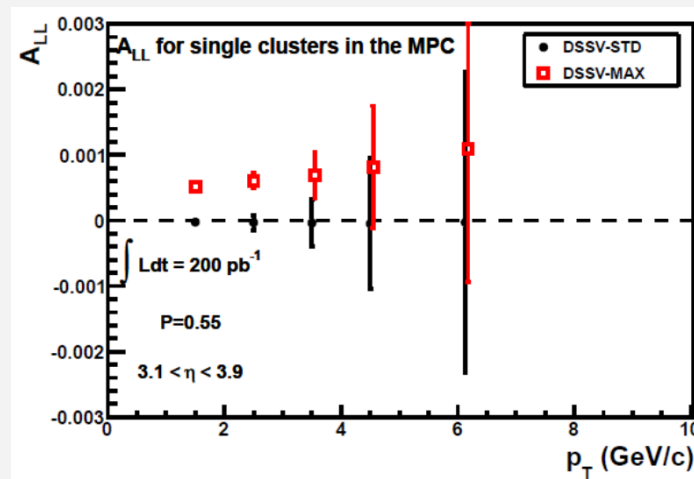
- Preliminary result for cluster asymmetry at  $\sqrt{s} = 200$  GeV



- Approximate cluster composition (from PYTHIA):



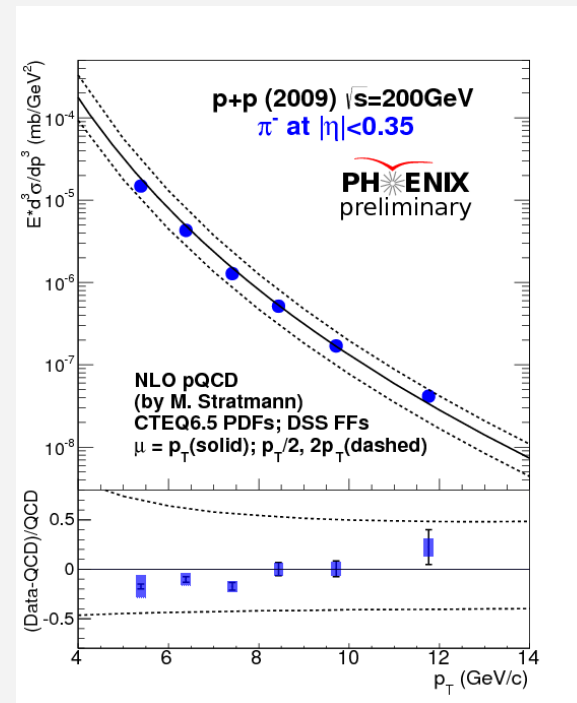
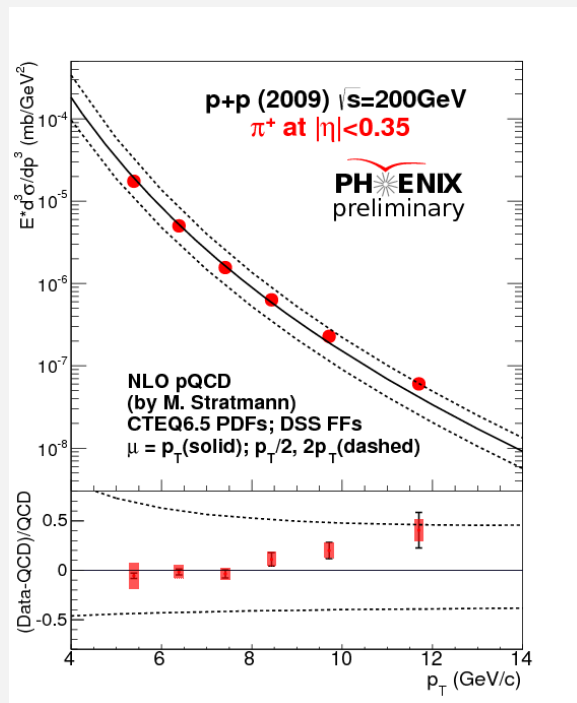
- Analysis of  $\sqrt{s} = 500$  GeV datasets underway
- Readout electronics and trigger upgrade for Run12
  - purity of trigger improved by factor 4
- Expected statistical uncertainty on cluster  $A_{LL}$  from *existing* 500 GeV data expected to be  $\sim 1e^{-4}$



# Probe: Charged Pions

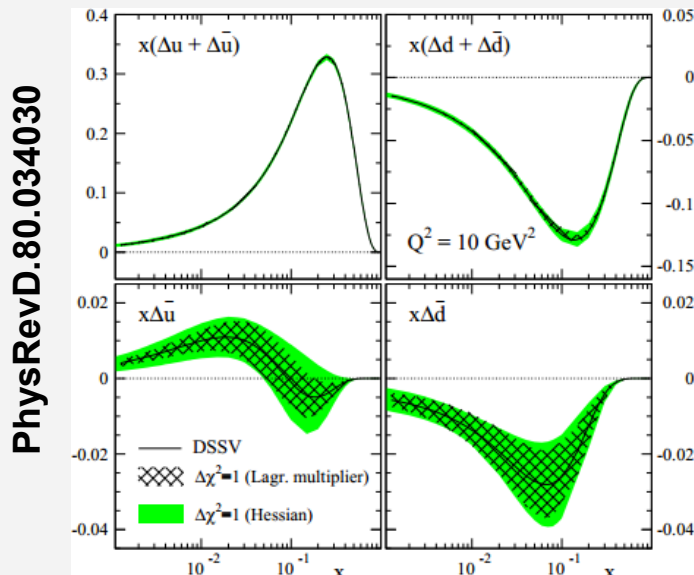
- Identified  $\pi^+$ ,  $\pi^-$ 
  - Ring Imaging Cherenkov Detector
    - electrons: 0.017 GeV/c
    - muons: 3.5 GeV/c
    - pions: 4.7 GeV/c

- Main source of BG:
  - conversions before DC, look like high  $p_T$  tracks
- Matching to HBD hit brings background to ~1% level
  - enables high  $p_T$  cross section measurement



# Probe: Charged Pions

- Valence quark content:  
 $\pi^+ = u\bar{d}$      $\pi^- = d\bar{u}$
- Plus large polarizations for u and d quarks:

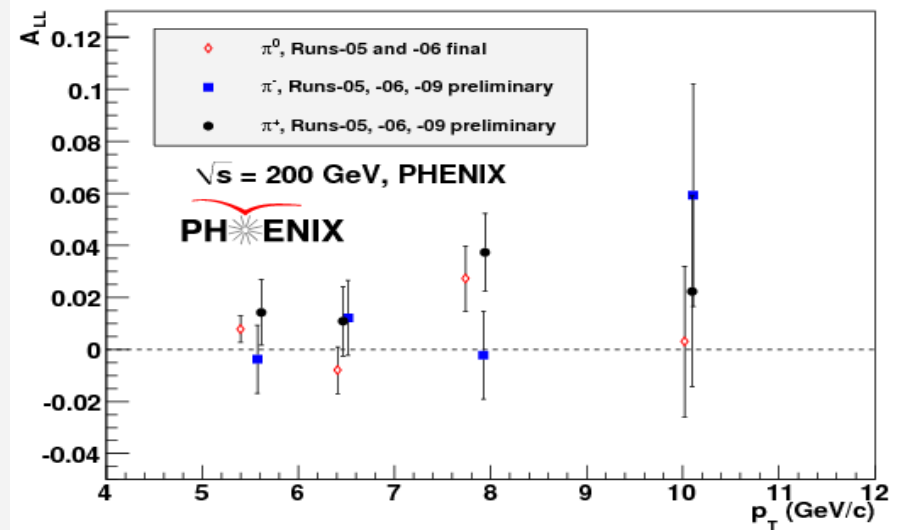


- Leads to  $\Delta G$  sign sensitivity:

$$A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-} \Rightarrow \Delta G > 0$$

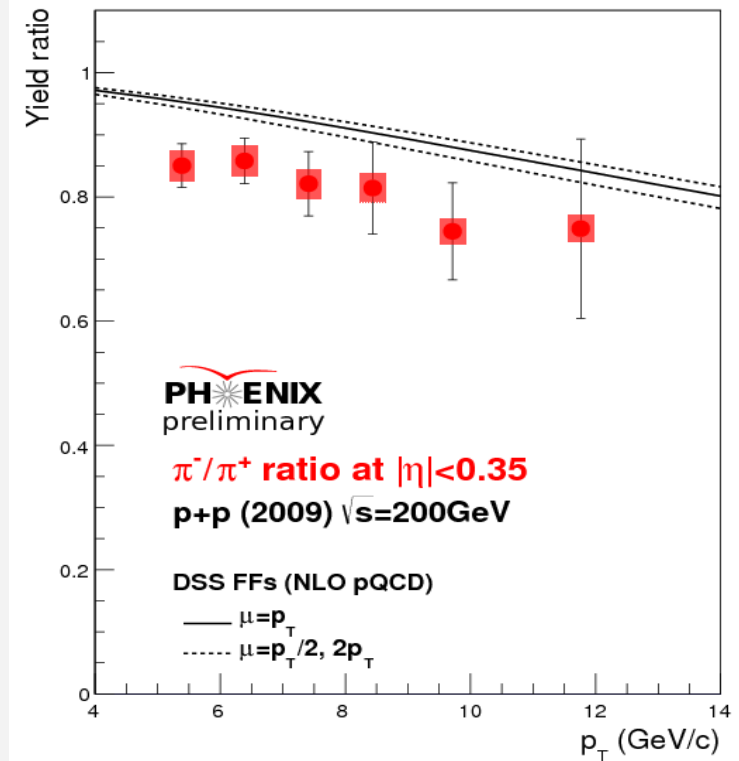
$$A_{LL}^{\pi^+} < A_{LL}^{\pi^0} < A_{LL}^{\pi^-} \Rightarrow \Delta G < 0$$

- Result without HBD
  - Tight EMCal shower shape and other cuts alleviate BG problem



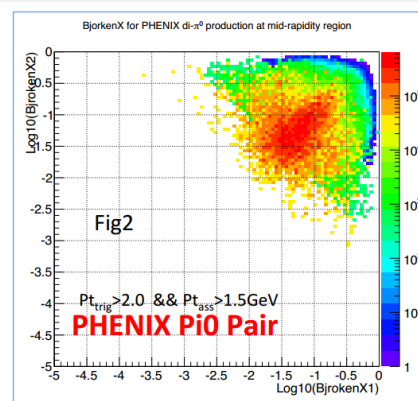
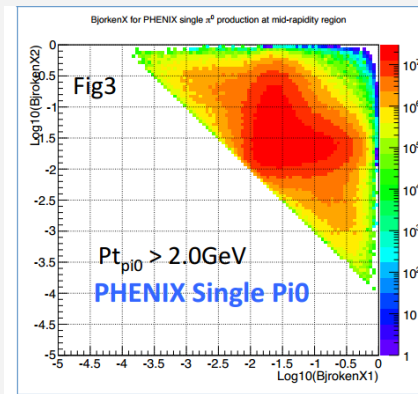
# Probe: Charged Pions

- Inclusion of “charge neutralized” average of charged pion  $A_{LL}$ s in global analysis already possible
  - lose sensitivity to sign of  $\Delta G$
- For full inclusion, fragmentation functions need to be updated to account for  $\pi^+$ ,  $\pi^-$  cross sections
  - global analyses needs to include high- $p_T$  p+p cross section measurements



# Probe: $\pi^0$ Pairs

- $\pi^0$ - $\pi^0$  correlation gives better Bjorken-x determination:

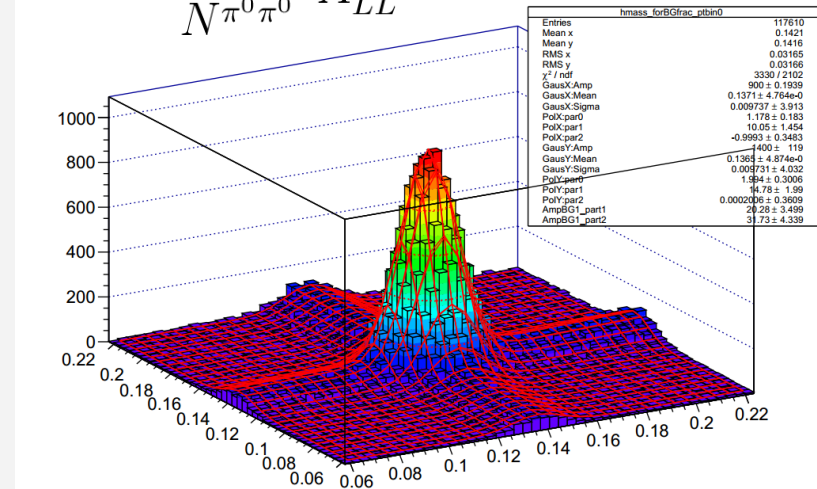


- Analysis similar to single inclusive  $\pi^0$  with an added dimension

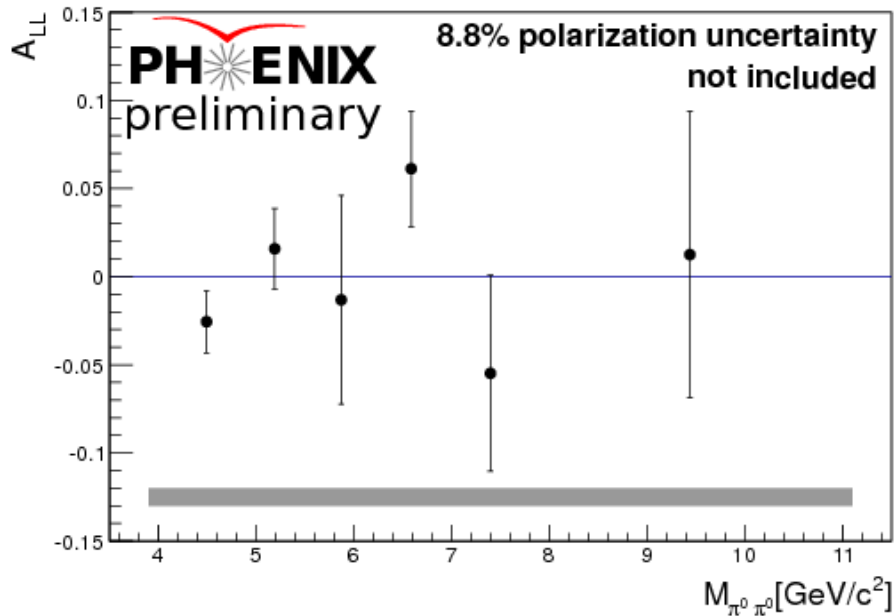
$$A_{LL}^{\pi^0\pi^0} = \frac{N^{\pi^0\pi^0 + \pi^0 BG + BG BG}}{N^{\pi^0\pi^0}} A_{LL}^{\pi^0\pi^0 + \pi^0 BG + BG BG}$$

$$- \frac{N^{\pi^0 BG}}{N^{\pi^0\pi^0}} A_{LL}^{\pi^0 BG}$$

$$- \frac{N^{BG BG}}{N^{\pi^0\pi^0}} A_{LL}^{BG BG}$$



# Probe: $\pi^0$ Pairs



- Statistics limited
- First pair correlation  $A_{LL}$  measurement in PHENIX
- Possible extensions to
  - $\pi^0$  + hadron
  - central arm  $\pi^0$  + forward cluster

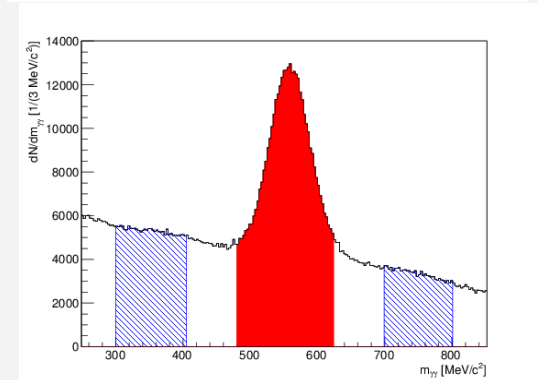
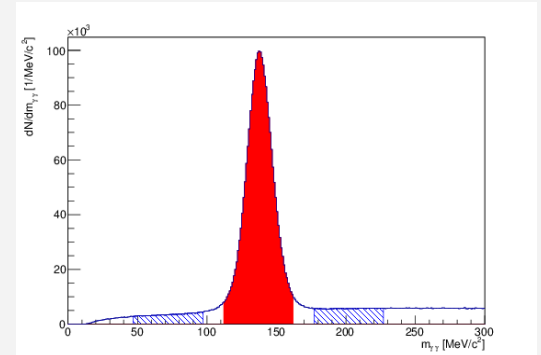
# Probe: Neutral Mesons

- Analyze through the  $\gamma\gamma$  decay channel
  - PHENIX EMCal
    - $\Delta\eta \sim 0.01$ ,  $\Delta\phi \sim 0.01$  rad. segmentation
  - B.R. 99% for  $\pi^0$ , 39% for  $\eta$
- Count signal region (red) and sideband region (blue) counts in ++ and +- helicity crossings:

$$A_{LL} = \frac{1}{P_B P_Y} \left( \frac{N^{++} - R N^{+-}}{N^{++} + R N^{+-}} \right), \quad R \approx \frac{N_{BBC}^{++}}{N_{BBC}^{+-}}$$

- Relative Luminosity R is measured using minbias BBC scalars
  - largest systematic uncertainty from confidence that BBC sees zero asymmetry
- Interpolate combinatorial B.G. shape under peak to get background fraction “r”

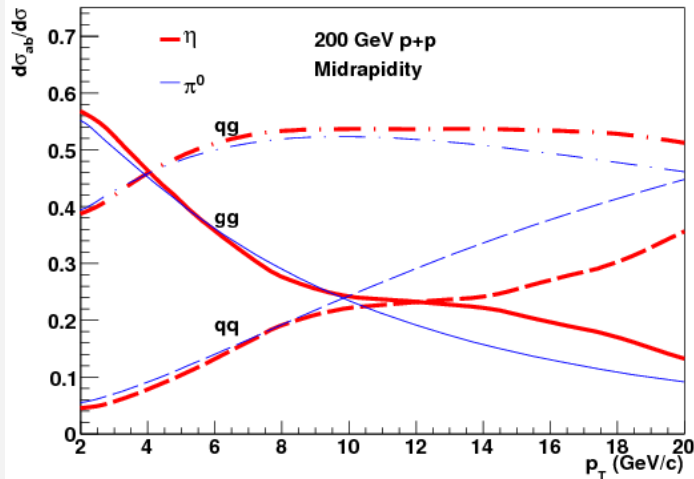
$$A_{LL}^{\pi^0} = \frac{A_{LL}^{signal} - r A_{LL}^{sides}}{(1 - r)}$$



## Advantage:

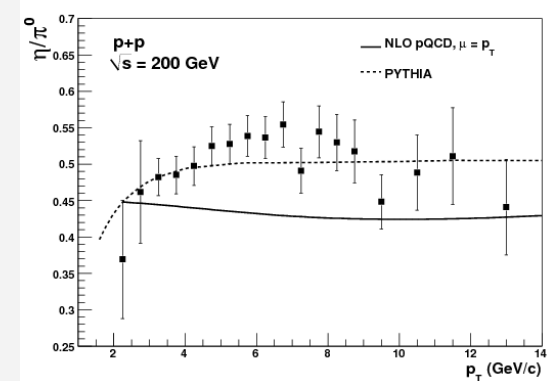
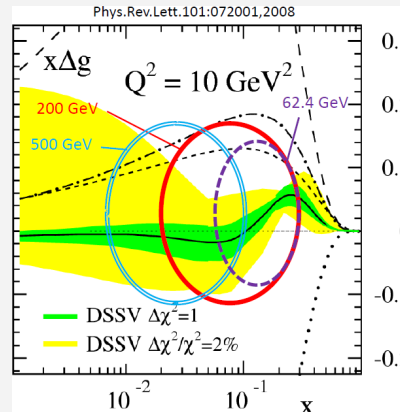
- identifiable mass peak
- choose cuts to minimize total uncertainty

# Probe: Neutral Mesons



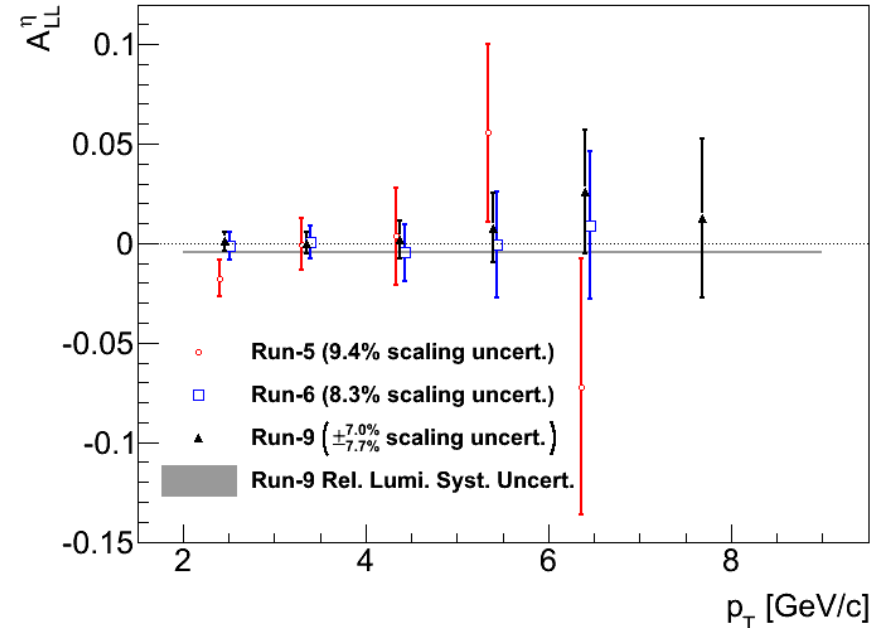
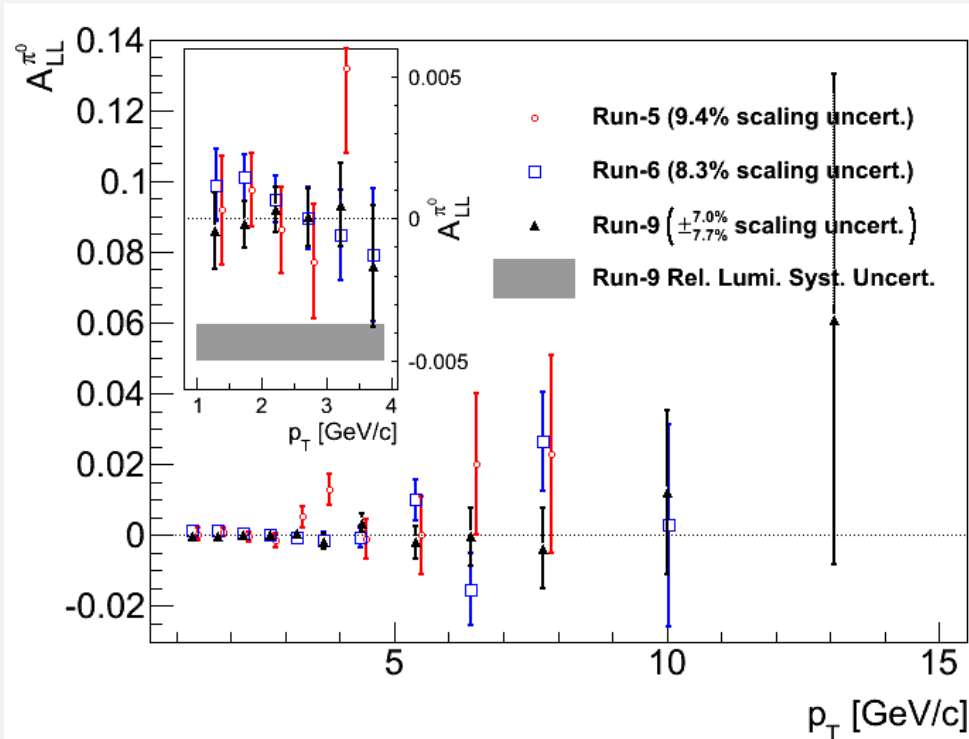
- q-g and g-g sub-processes at low  $p_T$
- $\pi^0$  is the highest statistics PHENIX central arm probe
  - excellent constraint of  $\Delta G$
- $\eta$  has larger decay opening angle, measurable to higher  $p_T$ 
  - $\pi^0$  decays merge  $\sim 10$  GeV/c
  - $\eta$  at  $\sim 40$  GeV/c

- $\sqrt{s} = 200, 62.4$  GeV PHENIX  $\pi^0$  currently used in global analysis
- $\sqrt{s} = 500$  GeV data under analysis
- inclusion of  $\eta$  requires more well-determined fragmentation functions in global analysis



# Probe: Neutral Mesons

- PHENIX Run9 Final results @  $\sqrt{s} = 200$  GeV
  - arXiv:1402.6296
- refinement of cuts
- addition of 12-15 GeV/c  $p_T$  bin for  $\pi^0$
- doubles existing statistics



# Systematic Uncertainties

- Relative Luminosity

$$A_{LL} = \frac{1}{P_B P_Y} \left( \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}} \right), \quad R \approx \frac{N_{BBC}^{++}}{N_{BBC}^{+-}}$$

- But is the BBC also sensitive to a physics  $A_{LL}$ ?

- Polarization measurement

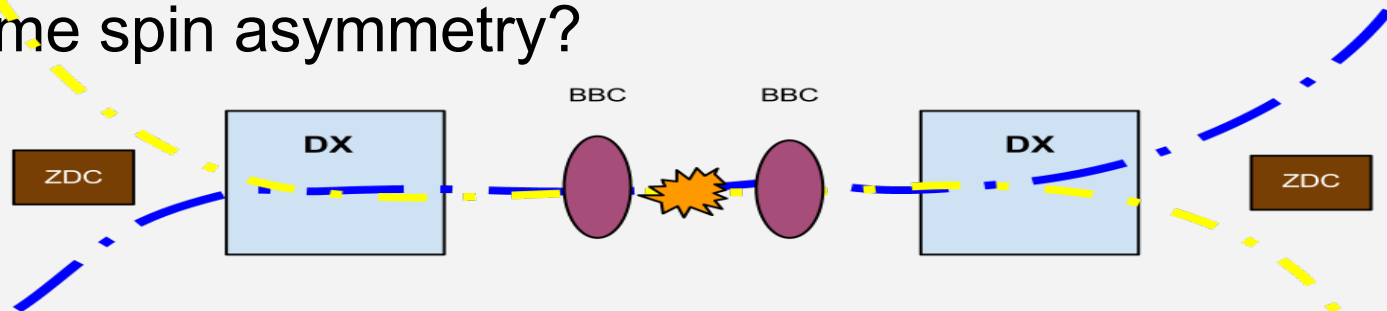
- Scale uncertainty, mostly from molecular hydrogen contamination of H-jet target and beam gas background
  - about 5% each

- Event overlap in the EMCal

- creates non-zero BG asymmetry that can depend on  $m_{\gamma\gamma}$
- controlled by cuts/careful binning of analysis

# Determination of Syst. Uncert. on RL

- i.e., what if our relative luminosity detector DOES see some spin asymmetry?



- We use our minimum bias BBC (Beam Beam Counter) to measure  $R$
- ...and compare it with a detector past the DX magnetic field
  - ZDC: Zero Degree Calorimeter, no charged particles
- We then assume the different physics they sample can't have the same asymmetry
  - so any non-zero asymm. in BBC should be apparent
- Compare the two results to get the best available estimate of systematic:

$$A_{syst} = \frac{1}{P_B P_Y} \frac{\left(\frac{N_{ZDC}}{N_{BBC}}\right)^{++} - \left(\frac{N_{ZDC}}{N_{BBC}}\right)^{+-}}{\left(\frac{N_{ZDC}}{N_{BBC}}\right)^{++} - \left(\frac{N_{ZDC}}{N_{BBC}}\right)^{+-}}$$

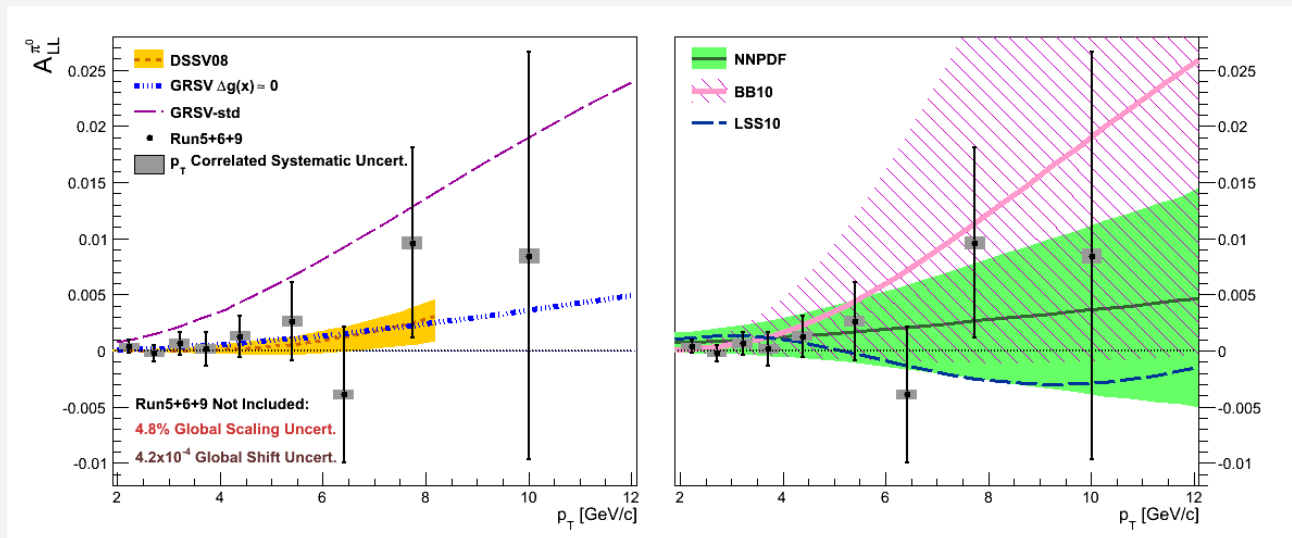
# RL Syst. Throughout the Years at $\sqrt{s} = 200 \text{ GeV}$

Run Year	$A_{LL}^R$ ( $10^{-3}$ )	$\Delta A_{LL}^R$ (stat+syst) ( $10^{-3}$ )
2005	0.42	0.23
2006	0.49	0.25
2009	1.18	0.21

- Take maximum overlap in  $A_{LL}^R$  as correlated
- Take also uncertainty on  $A_{LL}^R$  as part of systematic
  - 2009 total RL systematic uncertainty:  $1.4e^{-3}$
- More on relative luminosity studies later in the talk

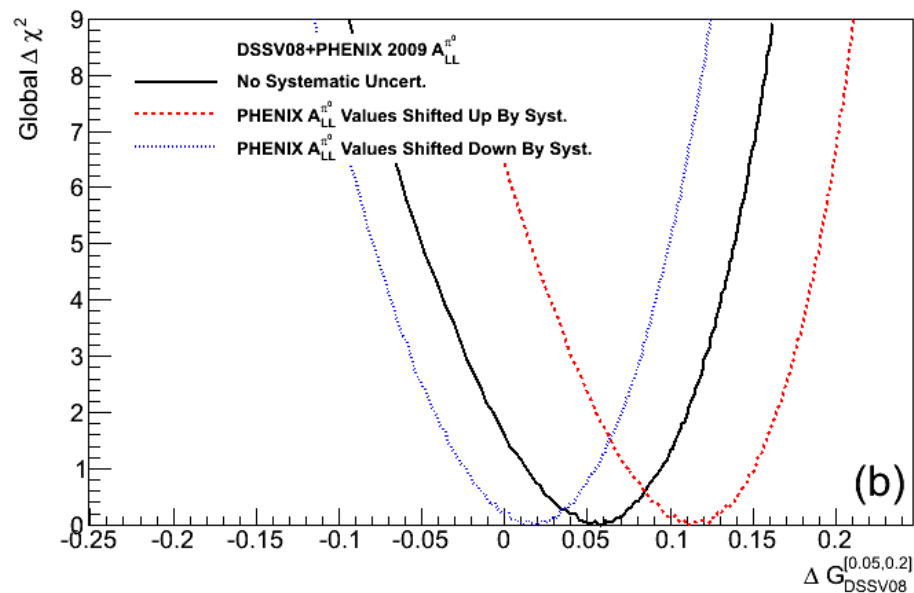
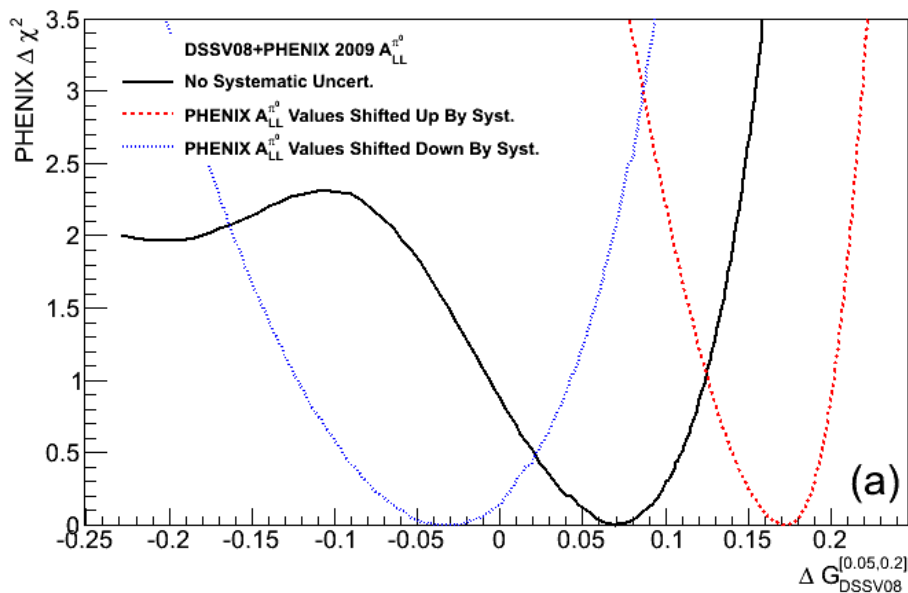
# Comparison of $\pi^0$ Results to Global Analyses

- Combined PHENIX results alongside various global analyses
  - DSSV08: DIS + SIDIS + PHENIX + STAR (up to 2006)
    - constrains  $\Delta G_{DSSV08}^{[0.05,0.2]} = 0.005^{+0.129}_{-0.164}$
  - GRSV: older DIS-only analysis
  - BB10: DIS-only analysis
  - NNPDF: DIS + prelim. STAR W  $A_L$ 
    - uses neural networks instead of PDF functional form
  - LSS10: DIS+SIDIS analysis

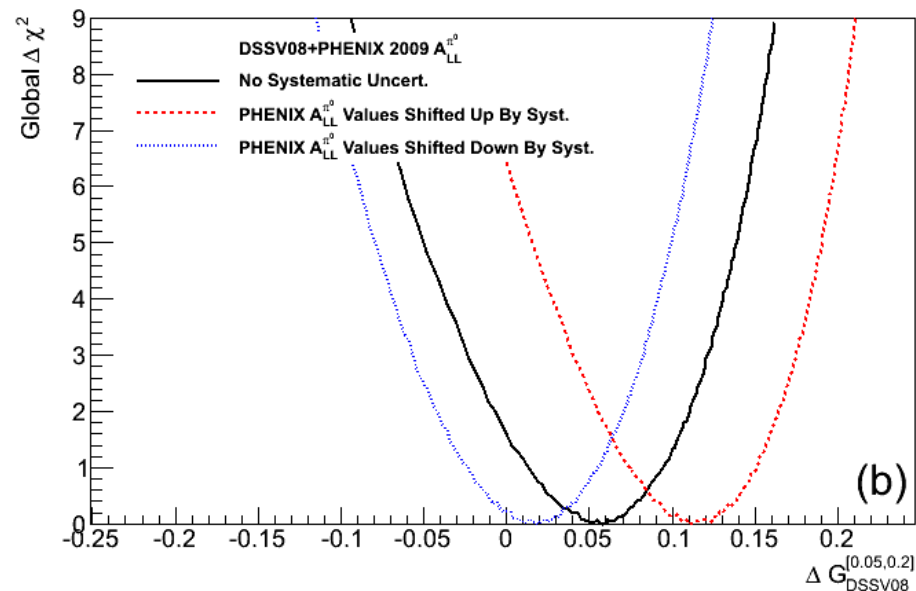
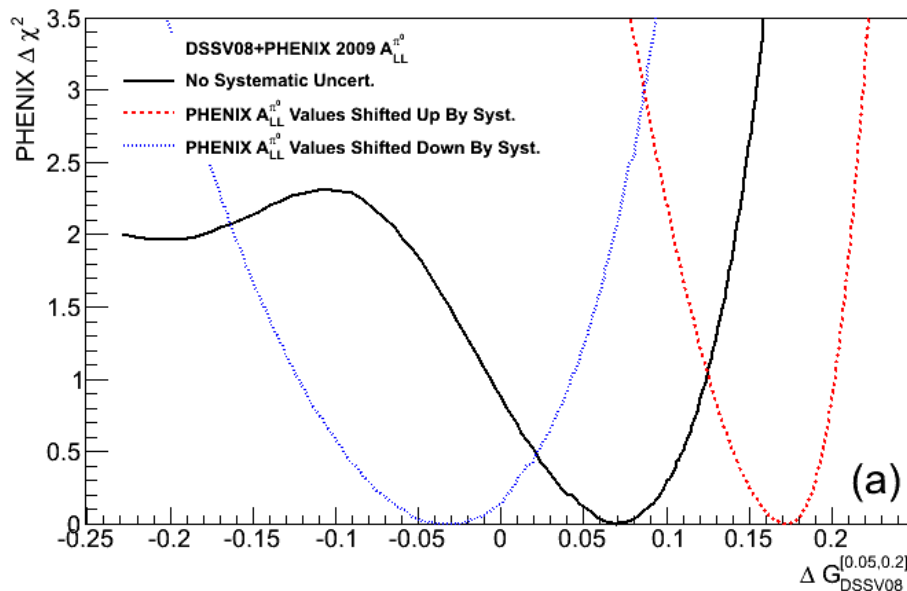


# Adding 2009 PHENIX Data, Effect of RL Systematic Uncert.

- Added 2009 PHENIX  $\pi^0 A_{LL}$  to the DSSV08 analysis
  - along with updates of some prelim data to final
- DSSV08 global analysis did not include systematic uncertainties from the experiments
- Effect of shifting only PHENIX  $\pi^0 A_{LL}$  up or down by its total systematic uncertainty
  - dominated by systematic uncertainty on relative luminosity



# Adding 2009 PHENIX Data, Effect of RL Systematic Uncert.



- Results of adding 2009 PHENIX  $\pi^0 A_{LL}$  to the DSSV08 analysis
  - along with updates of some prelim data to final:

$$\Delta G^{[0.05,0.2]} = 0.06^{+0.11}_{-0.15}$$

0.02

0.12

- vs. previously:

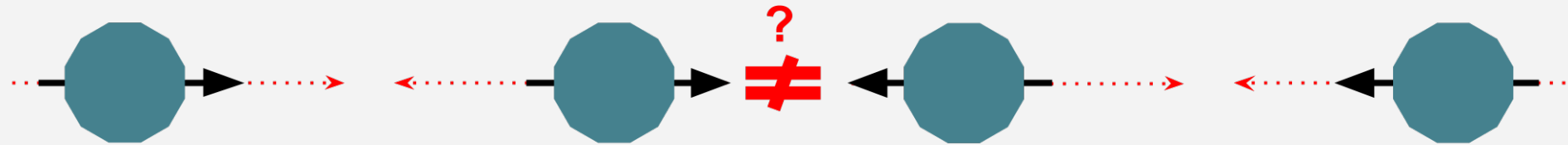
$$\Delta G_{DSSV08}^{[0.05,0.2]} = 0.005^{+0.129}_{-0.164}$$

# Relative Luminosity Studies

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# Issue: Non-physical Asymmetries

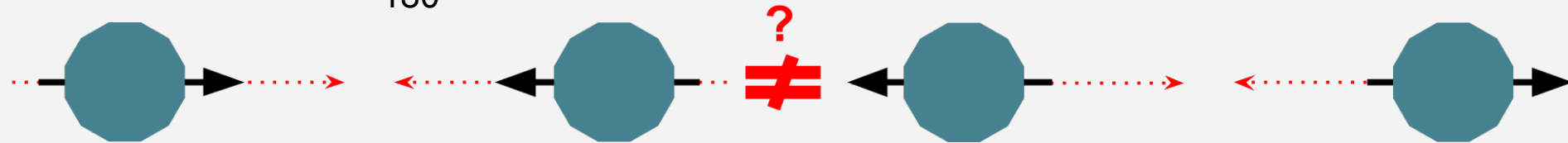
- Non-physical asymmetries seen in longitudinal running:
  - 180° rotation of the experiment:



■  $\epsilon_{PV} = 4.2 \pm 0.4 \times 10^{-4}$  in 2009

- Parity violating asymmetry:

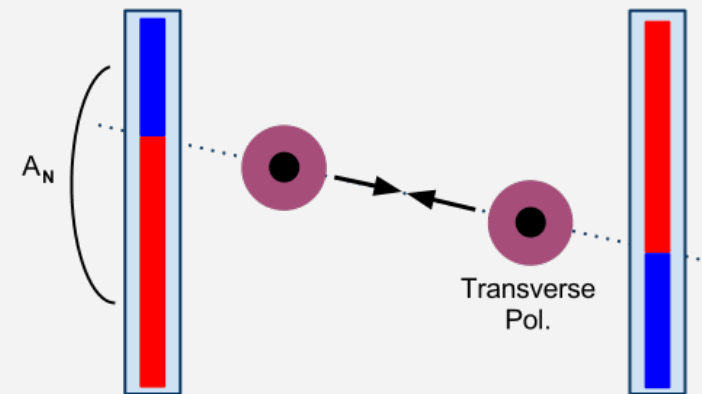
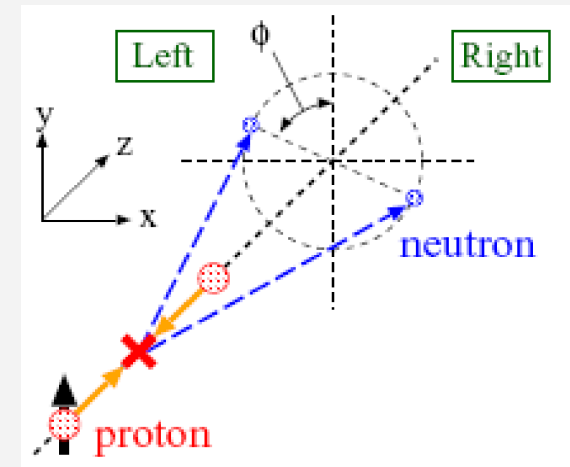
■  $\epsilon_{180} = 25.5 \pm 0.4 \times 10^{-4}$  in 2009



*Can these asymmetries be explained?*

# Transverse Spin Asymmetry $A_N$

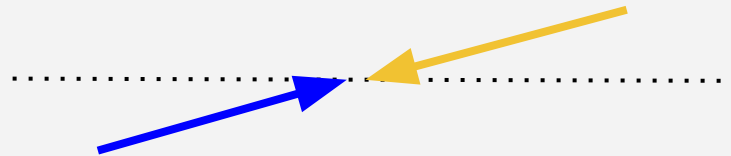
- No physics  $A_{LL}$ s we are familiar with in the ZDC or BBC
- But we do know of a transverse, phi-dependent, forward, single-spin asymmetry in **NEUTRON PRODUCTION**
  - transverse: Goes away for longitudinally polarized beams (local polarimetry)
  - phi-dependent: integrates out over all of phi
  - forward: backward asymmetry 0; polarization of other beam irrelevant
  - single-spin: scales as polarization  $P$  (compared to  $P^2$  for double spin asymmetries like  $A_{LL}$ )



# + Beam Geometry

- Beams traverse IRs in "zero" magnetic field region
  - straight paths
- Intersection geometry of beams can be decomposed into three components (x 2 planes)

- Collinear Angle:



- Offset:



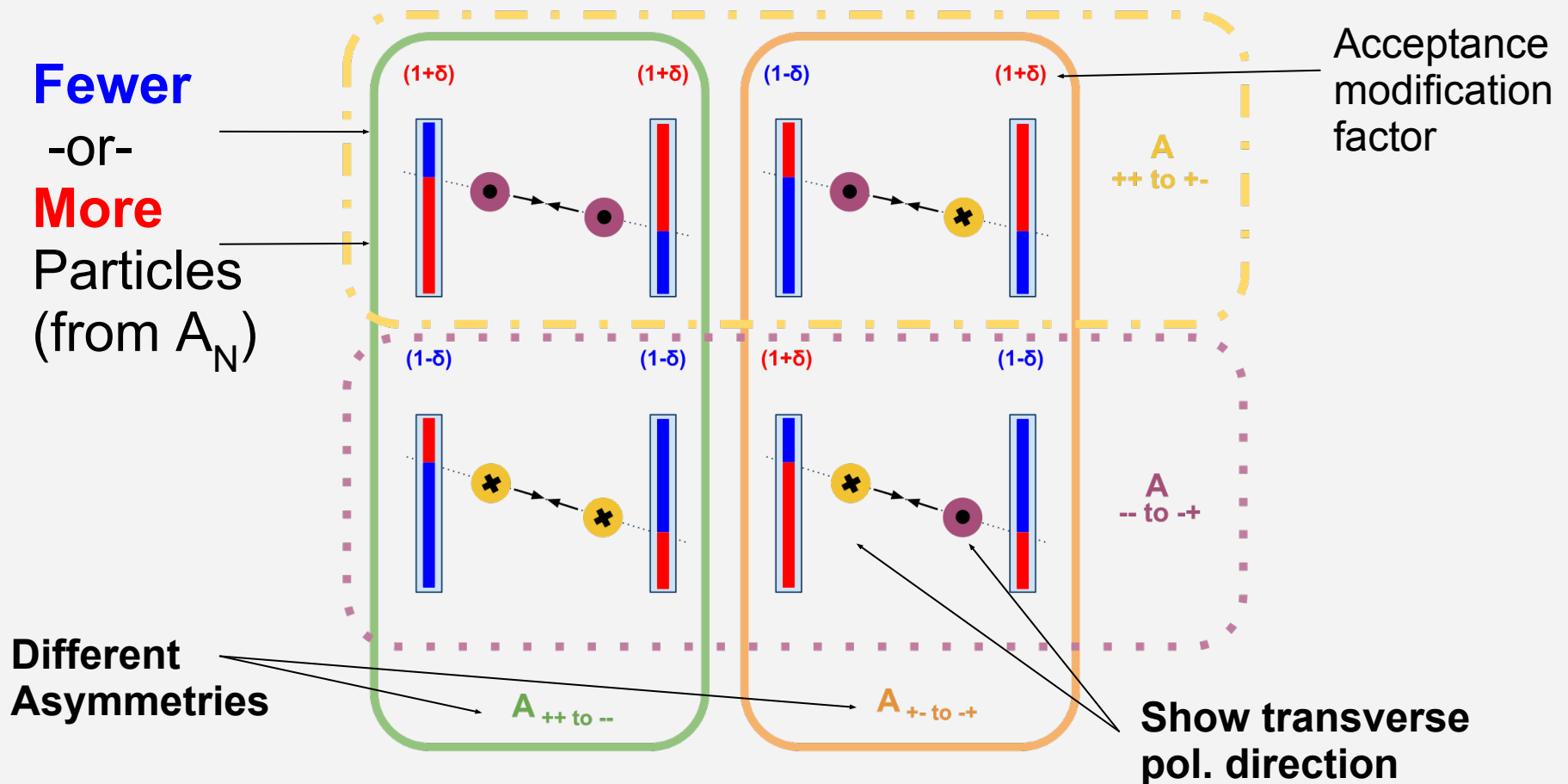
- Boost:



- Can measure all of these geometries with the *Beam Position Monitors*

# = False Asymmetries?

- Model for generation of various asymmetries

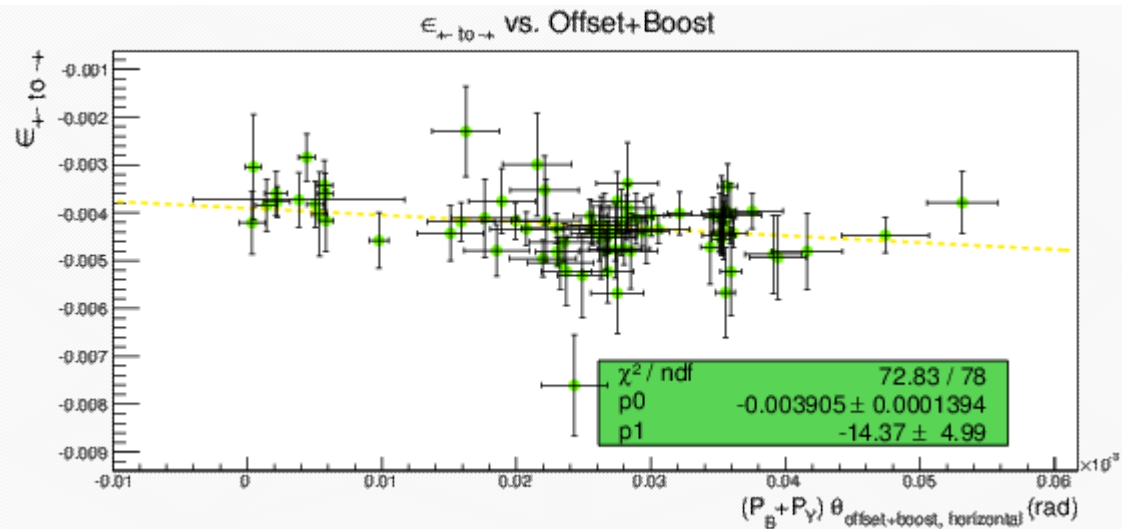
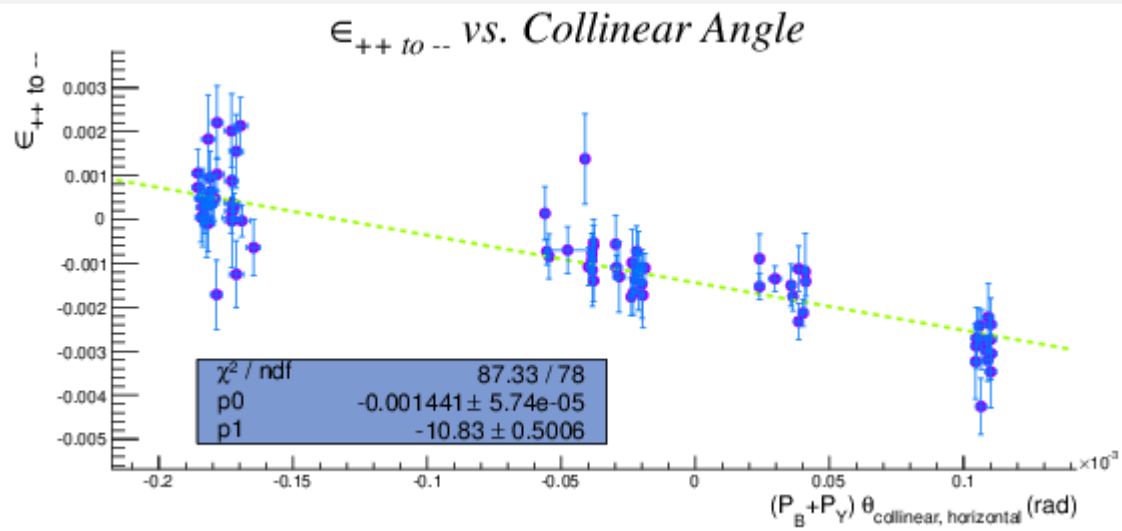


# Predictions of Model

	$\epsilon_{++ \text{ to } --}$	$\epsilon_{+- \text{ to } -+}$	$\epsilon_{++ \text{ to } +-}$	$\epsilon_{-- \text{ to } -+}$
Collinear Angle	$= (P_B + P_Y) \delta$	$= 0$	$= P_Y \delta$	$= -P_Y \delta$
Offsets	$= 0$	$= (P_B + P_Y) \epsilon$	$= -P_Y \epsilon$	$= P_Y \epsilon$
Boosts	$= 0$	$= (P_B + P_Y) \epsilon$	$= -P_Y \epsilon$	$= P_Y \epsilon$

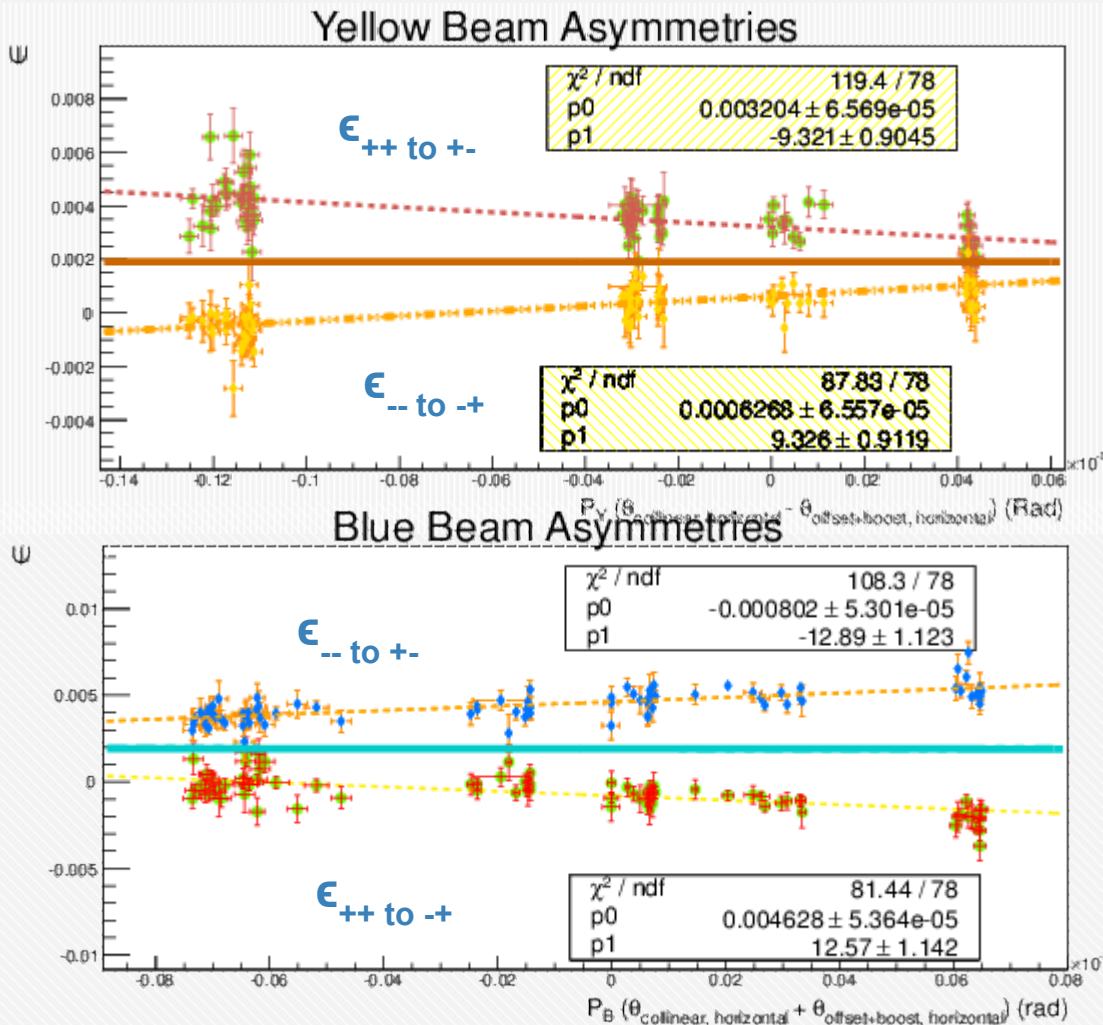
- Key Feature: linear dependence on polarization
- $\delta, \epsilon$ : acceptance modification factors, functions of angle, offset, or boost
- Important point: cross-check asymmetries which should be zero can be large under this effect!
  - failure to understand them would necessitate inclusion of additional systematic uncertainties

# Run 12 Collinear Beam Angle Scan



- Predicted to have largest variation in the Run12 scan of collinear beam angles
- Slope about  $\frac{1}{2}$  of simulation prediction
- Should not have changed much during scan
  - its dependence is on boosts and offsets

# Run 12 Collinear Beam Angle Scan



- Under model, these two yellow beam asymmetries should be equal and opposite
- Slopes equal and opposite, but not intercepts
- Same logic applies to blue beam asymmetries
- both yellow and blue asymmetries average to  $\sim 2\text{e-}3$ 
  - consistent with rest of Run12

# Remaining Unanswered Questions

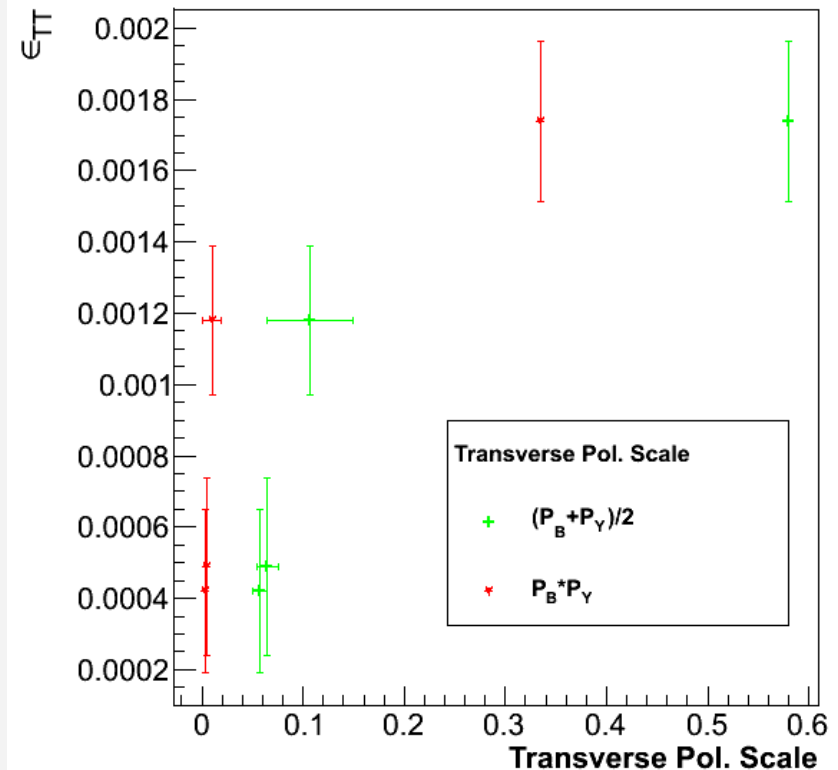
- Is the case of offsets/boosts analogous?
- Is there also an  $A_{\text{TT}}$ ?
- These studies lead to the decision to reduce the residual transverse polarization component at PHENIX in 500 GeV running
  - there we see a smaller ZDC/BBC asymmetry
  - no chance to confirm if such a change would also reduce it in 200 GeV running



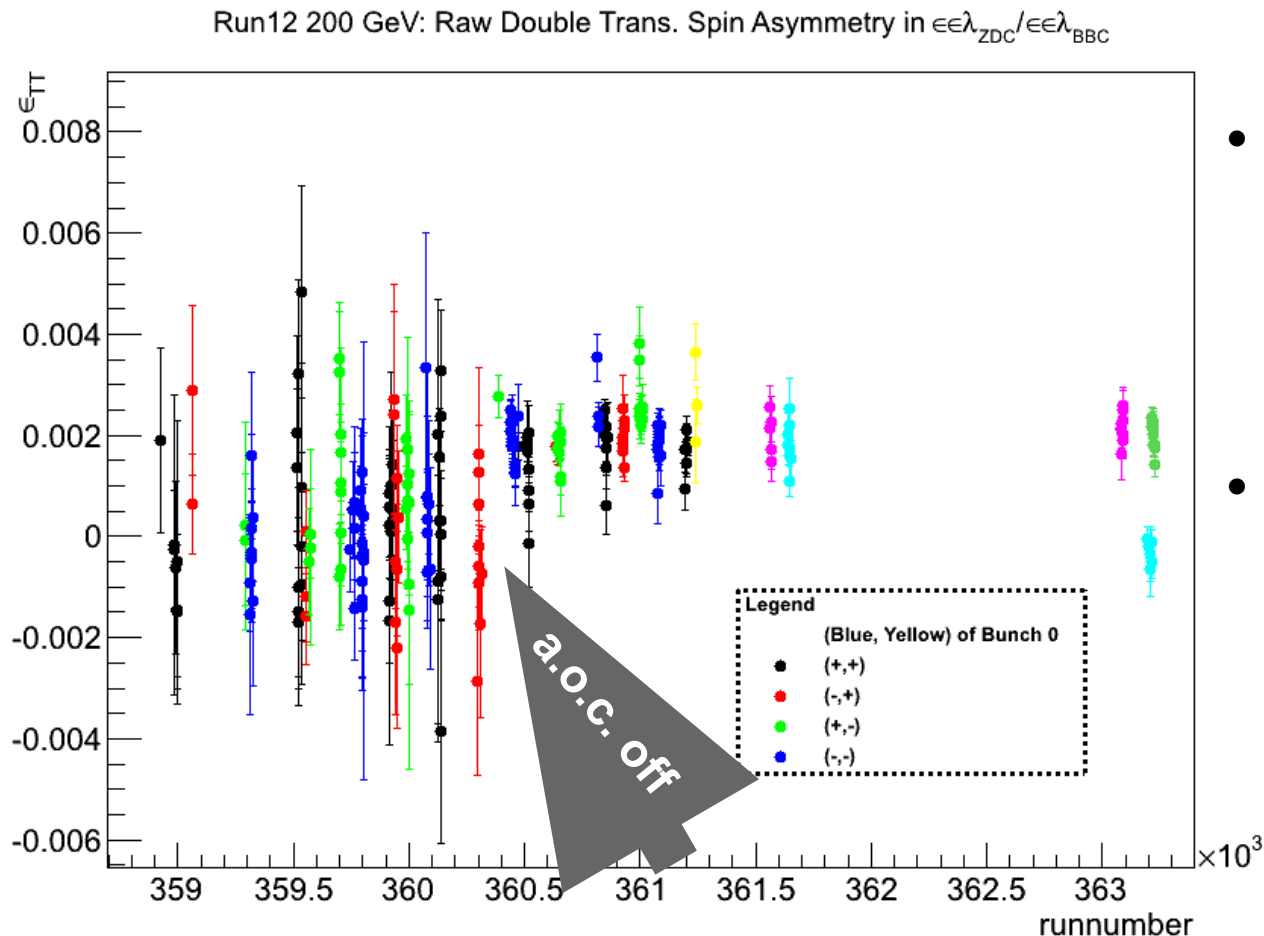
# Asymmetry in Transverse Running

- *Transversely* polarized running
  - much larger raw asymmetry,  $A_{TT} \sim 5.17e-3$  if scaled by transverse pol.

- Plot of 200 GeV asymms vs. transverse pol. hints at dependence
- Also have 500 GeV results with lower transverse pol *and* lower ZDC/BBC asymm



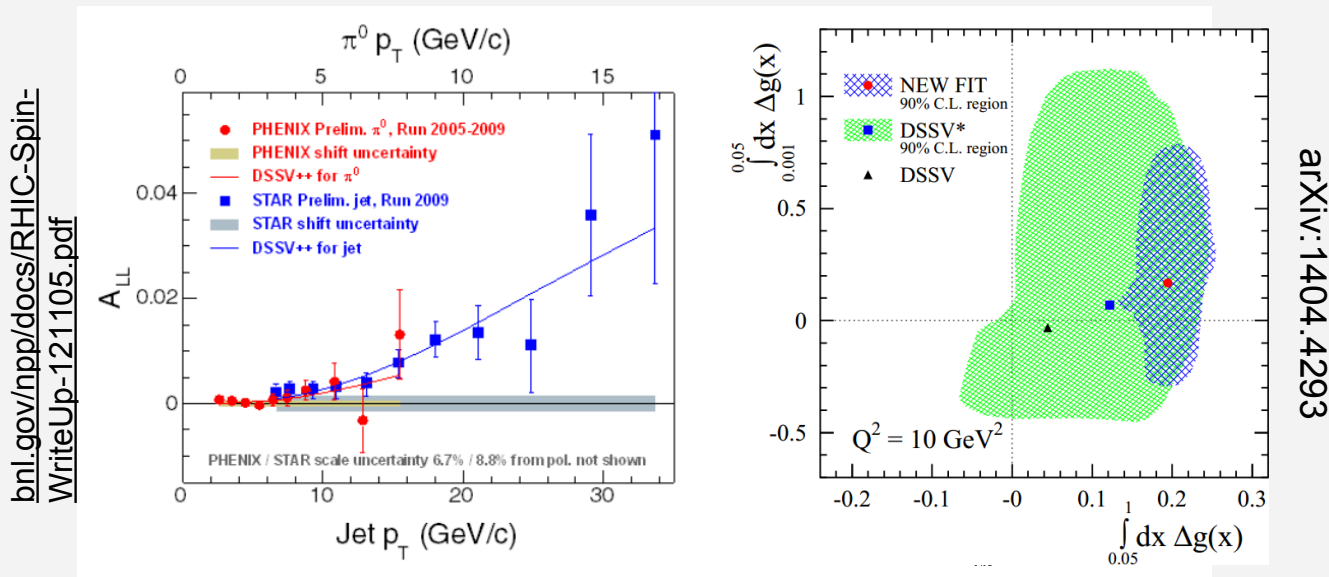
# Other Evidence of Beam Geometry Effects



- Accelerator physicists implemented automatic orbit correction for beams to help maintain polarization
- **increase** in average asymmetry/**decrease** in fluctuations coinciding with automatic orbit correction being turned **OFF**

# Conclusions

- 2009 PHENIX and STAR final data already swiftly included in the DSSV global analysis
  - important to fully treat experimental systematic uncertainties to get the full picture (plus theoretical uncertainties)
  - Other measurements + 500 GeV datasets can also be included



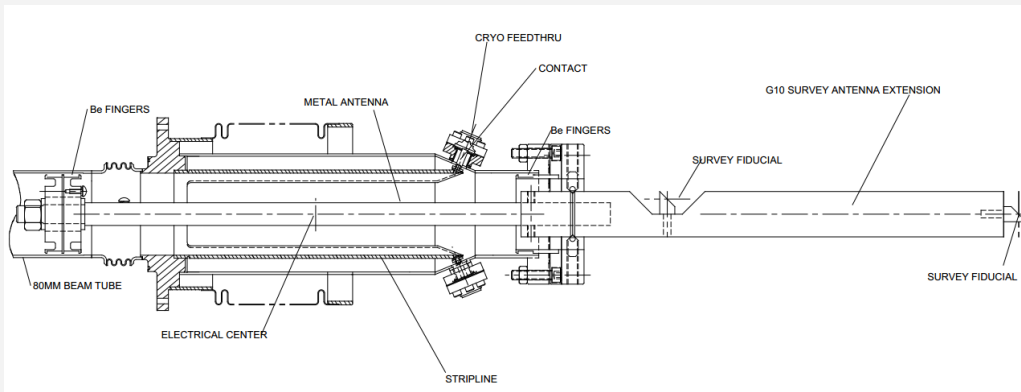
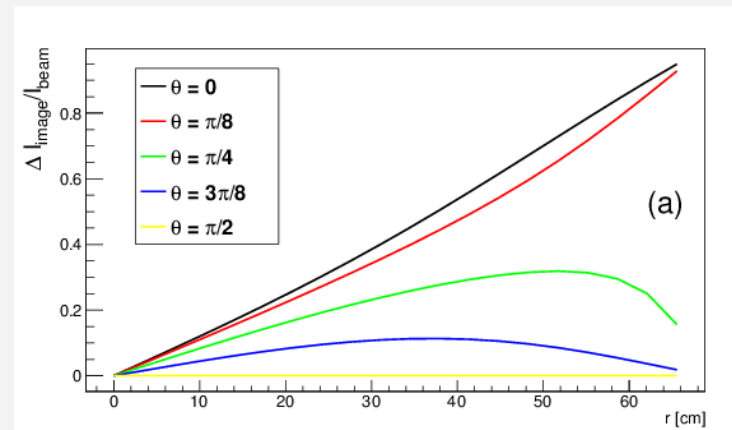
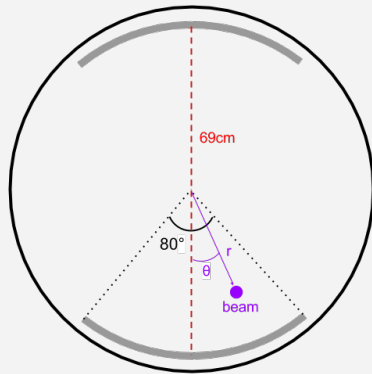
- Investigations into RL systematic uncertainty must continue
  - any further running w/ small transverse pol. component might help
  - we already understand much more than when we started, and have been able to avoid adding additional systematics
  - motivation for an  $A_{TT}$  measurement

# Backup

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# Beam Position Monitors

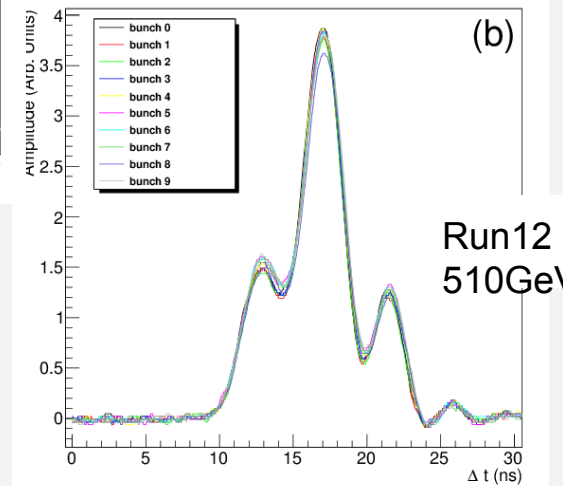
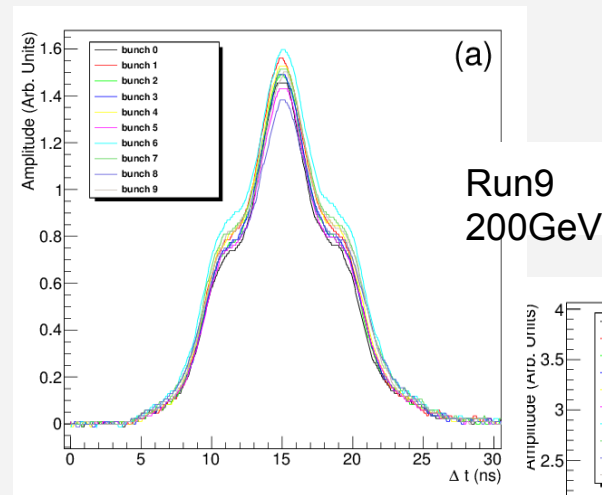
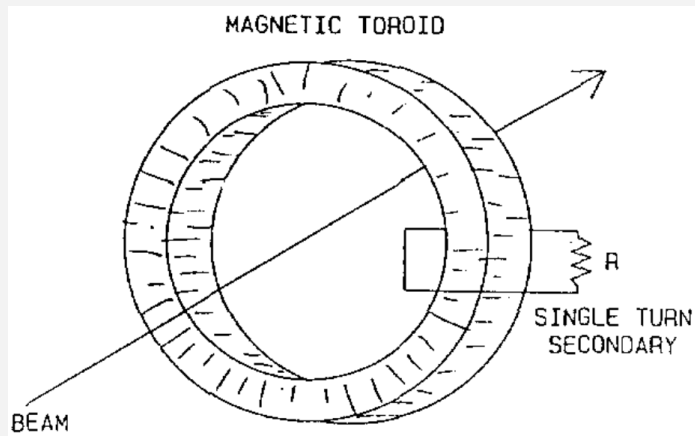
- Image current induced on two stainless steel striplines
  - Difference in current between sides a function of the beam deviation perpendicular to the striplines



- Electrical to mechanical center calibrated with antenna
  - uncertainty about 50 microns
  - similar uncertainty from frequency response

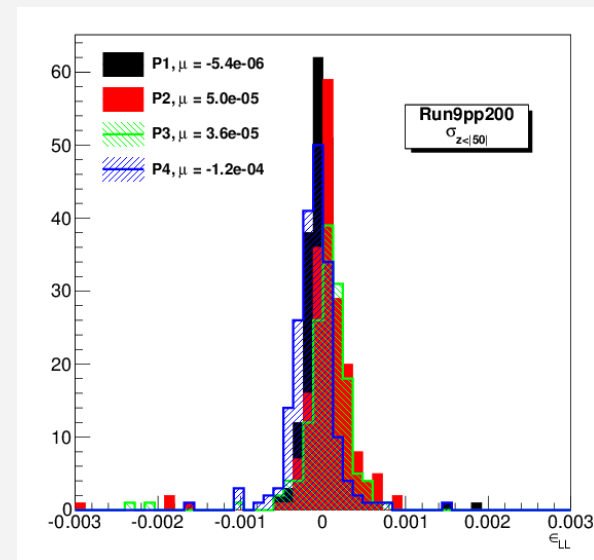
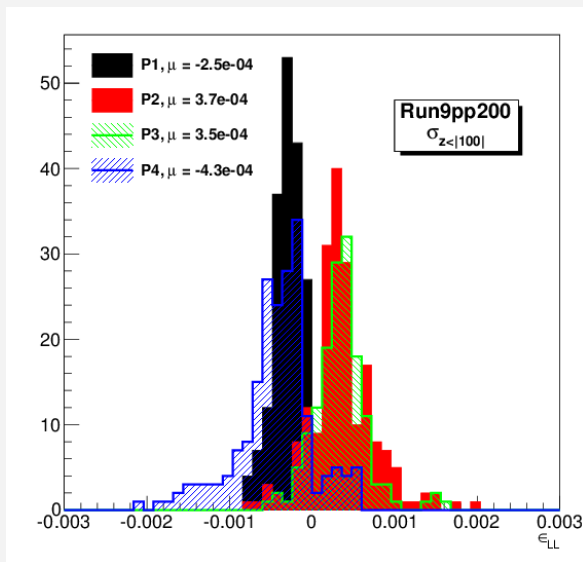
# Wall Current Monitors

- Measures the longitudinal profile of bunches in the ring
- Beam current passes through a magnetic toroid, induces voltage
  - covers large frequency range 3 kHz to 6 GHz



# WCM Bunch Width Asymmetries

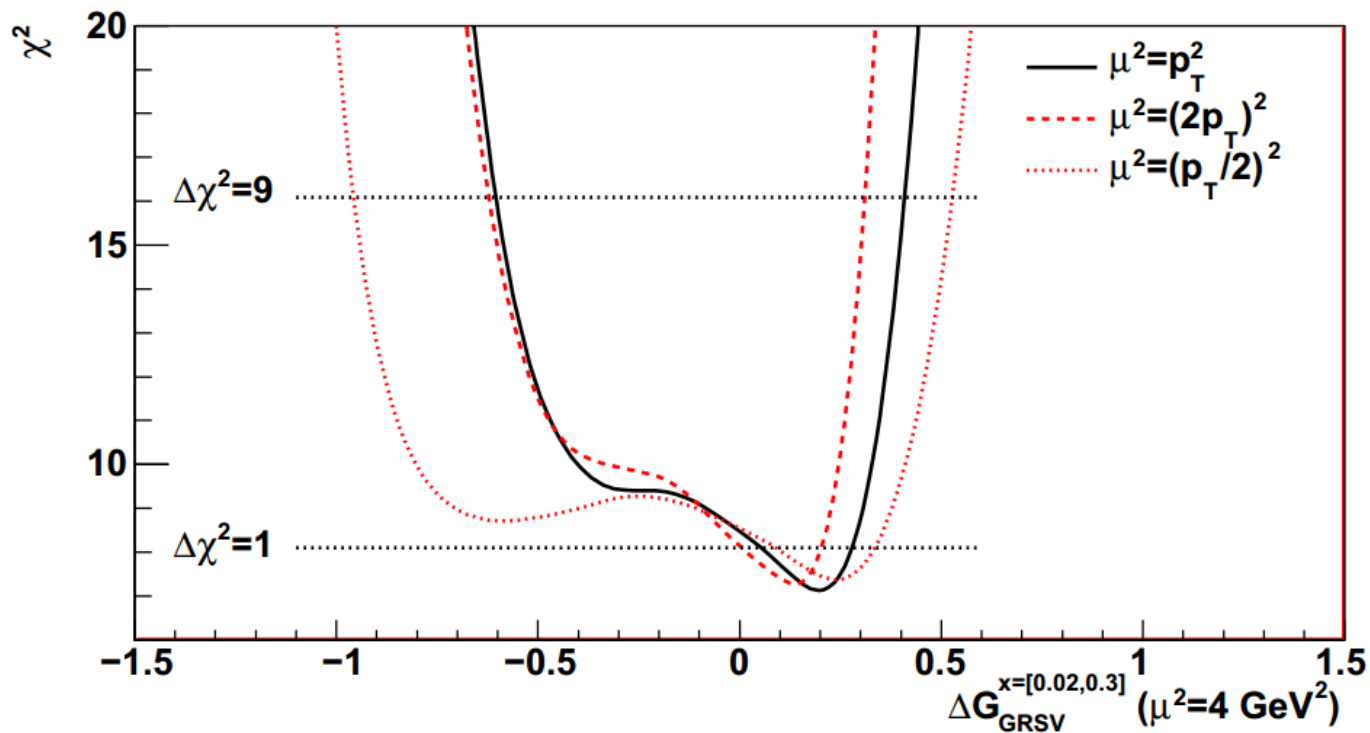
- Can convolute wall current monitor data to produce a longitudinal bunch distribution
- Then calculate double spin-dependent deviation from average bunch width:



- Significant asymmetry in width within  $|z| < 100$  cm
- Not observed in width within  $|z| < 50$  cm
  - could explain some of remaining spin pattern separation in rate-safe ZDC/BBC asymmetries

# Scale Uncertainties

- From Run6 result paper, showing effect of varying the theory scale uncertainties (factorization, fragmentation, normalization)
  - all set =  $p_T$  for the main analysis



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(2009)